3-D ultrasound imaging: a review

- Fenster, A. Downey, D.B.
Dept. of Diagnostic Radiol. & Nucl. Med., Univ. of Western Ontario, London, Ont., Canada

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Abstract:
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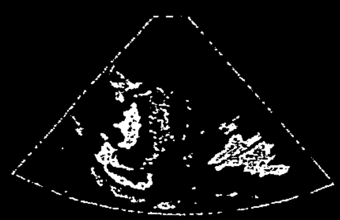

3-D Ultrasound Imaging: A Review

Aaron Fenster and Donal B. Downey
The John P. Robarts Research Institute, London, Canada, and Department of Diagnostic Radiology & Nuclear Medicine, The University of Western Ontario, London, Canada

We have recently passed the 100-year anniversary of the discovery of x-rays — a discovery that heralded a new way to visualize the body. In this technique, x-rays are directed at the body to produce a radiographic shadow of the 3-D structures within the body, which is recorded by a 2-D imaging detector such as film. The projection radiograph generated by this technique presents an image to the physician in which all 3-D information is lost. During the first 70 years after the discovery of x-rays, many attempts were made to develop imaging techniques in which some of the 3-D information within the body was preserved in the recorded image. In the early 1970s, computed tomography (CT) was introduced, revolutionizing diagnostic radiology. For the first time, 3-D information could be preserved in the recorded image and presented to the physician as a series of tomographic slices or sections of the body (i.e., 2-D images). In addition, for the first time in radiology, computers became central in the processing and display of the images. The availability of true 3-D information stimulated the field of 3-D visualization in diagnostic radiology with numerous applications [1-4].

The history of ultrasound imaging is much more recent. Following the pioneering work of Wild and Reid in the 1950s, the medical use of ultrasound progressed slowly, from A-mode systems to systems producing real-time tomographic images of anatomy and blood flow. The image quality of medical ultrasound has advanced sufficiently to make it an important and, at times, an indispensable modality in obstetrics and in the diagnosis and management of a large number of diseases. Nevertheless, ultrasound imaging still suffers from a number of disadvantages, and its full potential has not yet been realized.

The development of 3-D ultrasound imaging is a way to address the disadvantages of conventional ultrasound imaging. In this article we review approaches that have been attempted in the development of 3-D ultrasound imaging such as 3-D B-mode, color Doppler, and power Doppler systems. Acquisition, reconstruction, and rendering techniques for 3-D imaging are discussed, as well as applications and limitations.

Limitations of Conventional 2-D Ultrasound

One disadvantage of 2-D ultrasound imaging relates to the subjectivity of the conventional exam, which results from the dependence on the experience and knowledge of the diagnostician to manipulate the ultrasound transducer, mentally transform the 2-D images into a 3-D tissue structure, and make the diagnosis or perform an interventional procedure. This difficulty results primarily from using a spatially flexible 2-D imaging technique to view 3-D anatomy.

Ultrasound-guided therapeutic procedures are particularly affected because the process of quantifying and monitoring small changes during the procedure or over the course of time is severely limited by the 2-D restrictions of the conventional exam. This practice is time-consuming and inefficient and may lead to incorrect decisions regarding diagnoses and staging, and during surgery. In addition, it is difficult to localize the thin 2-D ultrasound image plane in the organ, and difficult to reproduce a particular image location at a later time, making the conventional 2-D exam a poor imaging modality for quantitative prospective or follow-up studies. Further, the patient's anatomy or orientation sometimes restricts the image angle, resulting in inaccessibility of the optimal image plane necessary for diagnosis.

The goal of 3-D ultrasound imaging is to overcome these limitations by providing an imaging technique that reduces the variability of the conventional technique and allows the diagnostician to view the anatomy in 3-D. Medical ultrasound imaging is inherently tomographic, thus providing information necessary for 3-D visualization. However, unlike CT and magnetic resonance (MR) imaging, in which the images are usually acquired at a slow rate as a stack of parallel slices,

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ultrasound provides tomographic images at a high rate (10-60 images per second), and the orientation of the images is flexible because they are not necessarily acquired as a stack of planes. In addition to the unique problems imposed by ultrasound imaging physics (speckle, shadowing, distortions), the high rate of image acquisition and flexibility of the conventional technique provide unique problems to overcome, as well as opportunities to be exploited in extending ultrasound imaging from its 2-D presentation of images to 3-D and 4-D.

Review articles describing the clinical utility of 3-D ultrasound imaging for use in radiology and echocardiology have been published [5-8]. These articles provide extensive lists of references and show that there have been numerous attempts at producing 3-D ultrasound systems by many investigators. These references show that there have also been many attempts to produce 3-D ultrasound imaging systems, which can be described simplistically by the four blocks shown in Fig. 1. The first block corresponds to the various acquisition techniques that have been employed. The second block deals with the recording of the ultrasound images prior to reconstruction. The third block deals with the reconstruction of the 3-D image from the recorded 2-D images. The final block represents the visualization technique used to display the 3-D image. All of these blocks are discussed in various sections to follow.

Acquisition Techniques

The flexibility of the image acquisition geometry makes the first component in the system (see Fig. 1) crucial for two reasons. First, since the series of tomographic images necessary for 3-D imaging can be acquired in arbitrary orientations, their relative position and angulation must be accurately known to avoid geometric distortions. Second, to avoid artifacts and distortions due to respiratory, cardiac, and involuntary motion, the image acquisition must be performed rapidly or gated appropriately. Three solutions have been proposed: free-hand acquisitions, mechanical localizers, and 3-D probes.

Free-hand Acquisition

In free-hand acquisition, the operator holds an assembly composed of the probe attachment, and manipulates it in the usual manner over the anatomy to be viewed. The images are acquired with arbitrary position and angulation under the operator's control. This technique offers special advantages because the operator can select optimal views and orientations, as well as accommodate complex patient surfaces. This unique advantage also places severe constraints on the 3-D system. To reconstruct the 3-D geometry properly, the exact relative angulation and position of the ultrasound probe must be known for each acquired image. In addition, the operator must ensure that when scanning the anatomy under investigation, no significant gaps are left. Three basic approaches to this tracking problem have been developed: acoustic, articulated arm, and electromagnetic positioners, as shown in Fig. 2.

Acoustic Positioner

The most common method for acquiring free-hand 3-D images is based on acoustic ranging, as shown schematically in Fig. 2a [9-16]. The angulation and position of the transducer is obtained by mounting three sound-emitting devices (e.g., spark gaps) in a fixed position relative to each other on the transducer. An array of microphones is typically mounted above the patient. To obtain the information necessary to reconstruct the 3-D image, the operator moves the transducer freely over the patient while the sound emitting devices are active. With knowledge of the speed of sound in air, the positions of the microphones, and the measurements of the time-of-flight of the sound pulses, the

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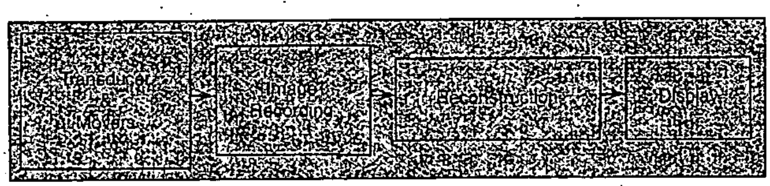
position and angulation of the transducer can be continuously monitored. Clearly, to obtain useful data, the microphones must be placed around the patient in a manner that provides unobstructed lines of sight to the emitters, and they must be sufficiently close to the transducer to be able to detect the pulses of sound. In addition, corrections must be made for variation of the speed of sound in air due to changes in temperature and humidity.

Articulated Arm Positioner

The simplest approach is achieved by mounting the transducer on a mechanical arm system with multiple movable joints, which allow the operator to manipulate the transducer in a complex manner and select the desired view and orientation (see Fig. 2b) [17-20]. Potentiometers are located at the joints of the moveable arms so that any angulation of the joints is measured and recorded. From these measurements, the position and angulation of the transducer can be continuously calculated and monitored.

This approach has been implemented in a number of ways, primarily for echocardiographic measurements of ventricular volume [17-19, 21]. Some of these implementations restrict the motion to one axis for increased precision, while others allow complete freedom. Precision is improved by keeping the individual arms as short as possible; however, this restricts the imaged volume.



1. Schematic block diagram showing the four stages of the 3-D ultrasound imaging system. The first stage refers to the imaging acquisition hardware used to manipulate the ultrasound transducer; the second, to the manner in which the 2-D ultrasound images are recorded; the third, to the reconstruction technique used to obtain the 3-D image; and the fourth, to the display technique used to visualize the 3-D image.

Magnetic Field Sensor

Another approach makes use of a six degree-of-freedom magnetic field sensor (Polhemus Fastrack, Colchester, VT; Flock-of-Birds, Ascension Technologies) to measure the transducer's position and orientation [22-25]. This device, shown schematically in Fig. 2c, consists of a transmitter placed close to the patient and a receiver mounted on the probe. The transmitter produces a spatially varying magnetic field, and the receiver, containing three orthogonal coils, measures the field strength. By measuring the local magnetic field, the position and angulation of the receiver relative to the transmitter can be determined. Typically, field measurements are made at 100 Hz, thus allowing continuous monitoring of the ultrasound transducer. The receiver size is about 16 cm^3, allowing for easy mounting on the ultrasound transducer without interference with its usual use.

Although this approach is very flexible, accurate 3-D reconstruction requires that electromagnetic interference be minimized, the transmitter be close to the receiver to allow field measurements with sufficient signal-to-noise ratio (SNR), and that ferrous or highly conductive metals be absent from the vicinity, since they can distort the magnetic field. These limitations can be overcome with special precautions, yielding high quality images, typically in obstetrics and vascular imaging [24, 26-28].

The most common method for acquiring free-hand 3-D images is based on acoustic ranging.

Mechanical Localizers

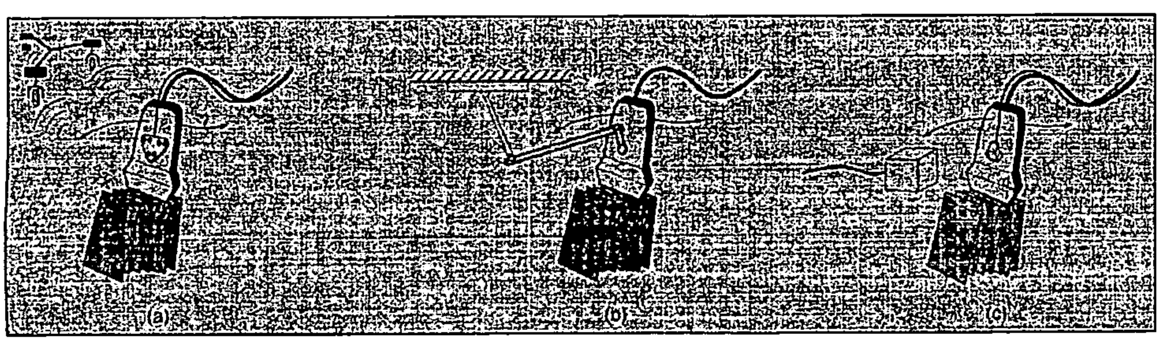
Although the free-hand 3-D scanning approach offers great flexibility, problems of noise and scanning gaps may reduce the image quality, particularly when imaging small structures at high resolution. One way to avoid these problems is to use a mechanical 3-D probe in which the third dimension is obtained by mechanical movement of the transducer in a precise, predefined manner. As the transducer is moved, 2-D ultrasound images are acquired at predefined spatial intervals so that the imaging sequence samples the volume of interest properly, without missing any regions. A number of investigators and commercial companies have developed various kinds of mechanical 3-D probe assemblies. In general, these assemblies make use of conventional mechanical or linear-array transducers mounted in an assembly to allow translation or rotation of the transducer by a motor. When the motor is activated (typically under computer control), the transducer rotates or translates, sweeping rapidly (if appropriate) over the region being examined. Since the scanning geometry is predefined by the scanning assembly, no external frame of reference is necessary. The reconstruction is efficient because the required geometrical parameters can be computed in advance.

The sizes of the assemblies vary from small integrated mechanisms that house the motor and transducer, providing an integrated 3-D probe, to mechanisms employing a motor attached to an external fixture that houses a conventional 2-D ultrasound transducer. The small integrated 3-D probes allow easier use by the operator; however, their use requires the purchase of a special ultrasound system. External assemblies result in bulkier devices, but by using existing 2-D transducers, they obviate the need to purchase an expensive new ultrasound machine to obtain 3-D imaging capability. This approach to 3-D imaging has been implemented with three basic types of motion, as shown schematically in Fig. 3: linear, fan, and rotation scanning.

Linear Scanning

In this approach, the conventional ultrasound transducer is mounted on an assembly connected to a lead screw that can be driven by a motor (Fig. 3a). Rotating the lead screw moves the transducer in a linear fashion, parallel to the patient's skin and perpendicular to the image plane. The transducer can be tilted to allow for 3-D color Doppler imaging. In addition, the spatial-sampling frequency of image acquisition (i.e., stepping or sampling interval) can be adjusted based on the elevational resolution of the transducer, so that the region of interest at a particular depth is sampled properly. Since the acquired 2-D images are parallel to each other and separated by predefined intervals, the reconstruction can be very efficient. Downey, et al. [29], demonstrated a linear scanning system in which the 3-D image was available for viewing in less than 0.5 seconds after acquisition of 200 images, each of which was 336 x 352 pixels.

Successful applications of linear scanning for vascular imaging using B-mode [30-34], color Doppler [24, 35-41], and Doppler power imaging [30, 31] have been reported. These results demonstrate



2. Schematic diagram showing three basic methods for obtaining the position and orientation of the ultrasound transducer for the free-hand acquisition technique: a) acoustic, b) articulated arm, and c) electromagnetic positioners.

There are many techniques for displaying 3-D images.

the advantages of the flexibility offered by linear spatial-sampling, allowing minimal degradation of information in the 3-D images. Others have also used this approach in echocardiology, using a transesophageal approach with a horizontal scanning plane. The 3-D image was obtained as a stack of planes generated by mechanically withdrawing of the probe (pullback technique) [42-44].

Fan Scanning

In this scanning geometry, the transducer (and hence the imaging plane) is rotated about an axis at the transducer face, as shown in Fig 3b. This results in an angular sweep, providing a fan of planes, which are acquired with a predefined angular separation [24, 45-49]. In systems using an external assembly, the transducer does not move across the skin, but is made to pivot at the point of contact with the skin. This simple approach lends itself to compact designs for both the external assemblies, as well as the integrated 3-D transducers. Acoustic Imaging Corp. (Phoenix, Arizona) and Kretztechnik (Zepf, Austria) have demonstrated integrated 3-D transducers for use in abdominal and obstetrical imaging. Successful applications in echocardiology by TomTec Inc. (Munich, Germany) have been achieved using a transesophageal approach in which the imaging plane is vertical (i.e., parallel to the axis of the probe) or horizontal [50], and the probe is rotated by an external motor assembly, with the axis of rotation along the central axis of the probe [51, 52].

The advantage of this technique is that the mechanism (both the external and integrated assemblies) can be made sufficiently small to allow easy hand-held manipulations. Because the angular step between acquired planes is fixed, the distances between sampled regions depends on depth. Near the transducer, where the elevational resolution is fine, the sampling distances are small, while in the far field, where the elevational resolution is poor, the sampling distances are large. Thus, the resolution in the 3-D image is not isotropic, but degradation can be minimized by appropriate selection of the angular scanning interval.

Rotational Scanning

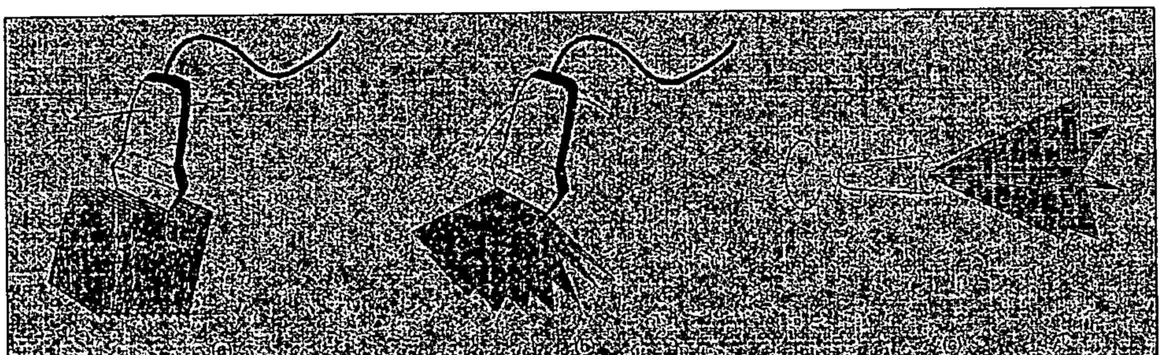
In this scanning geometry, the transducer is placed into an external assembly that rotates the probe with the axis of rotation along the central axis of the probe (Fig. 3c). In this way, the probe tip and its axis location remain fixed, and the acquired images sweep out a conical volume in a propeller-like fashion [24, 31, 53-58]. As in the fan acquisition approach, the angular step is also fixed, resulting in a spatial sampling distance that increases away from the rotational axis. Thus, the resolution varies in the 3-D image in a complicated manner. In general, the resolution degrades axially, due to degradation in the elevational resolution of the 2-D image, and also degrades in the perpendicular direction (away from the axis of rotation), due to sparser spatial sampling resulting from the fixed angular step.

With this approach, the acquired planes intersect in the center of the volume along the axis of rotation. If any motion occurs during the scan, other than the desired rotation about the probe axis of either the patient or the probe, then the acquired planes are not consistent (i.e., 0° and 360° images will not be the same), and the resulting image would contain artifacts in the center along the axis of rotation. In addition, the relative geometry of the imaging plane and the axis of rotation must be accurately known to avoid artifacts. Specifically, the tilt, or the offset from the rotation axis of the imaging plane, must be known, and corrected, to avoid significant artifacts at the center of the image.

2-D Arrays

The techniques described above all use 2-D images generated by conventional ultrasound transducers, in conjunction with mechanical or electronic 2-D scanning. Information about the third dimension is achieved by physical movement of the transducer, either using mechanical means, or by the hand of the operator. A different approach is being developed that makes use of a 2-D transducer array, which is shown schematically in Fig. 4 [59-65].

Information about the third dimension is achieved by replacing physical movement of the transducer by electronic scanning. In this approach, the 2-D array generates a pulse of ultrasound diverging away from the array in a pyramidal shape. The echoes are processed to generate 3-D



3. Schematic diagram showing the three basic types of motion used in 3-D ultrasound systems making use of mechanical scanning: a) linear, b) fan, and c) rotational.

information in real time. These types of transducers will allow real-time echocardiographic 3-D imaging. Although this approach is in its early stages of development, and substantial work is required to allow routine use, it may well represent the ultimate approach for most 3-D ultrasound image acquisition. This is reminiscent of the transition in 2-D imaging from mechanical transducers to electronic phased arrays. However, before these 2-D arrays become practical, a number of problems must be overcome related to low yields resulting from the manufacture of a large number of small elements, along with the connecting and bundling large number of leads.

Intravascular 3-D Ultrasound

2-D intravascular ultrasound (IVUS), has been demonstrated to be a useful technique for direct assessment and planimetric measurement of vascular dimensions and atheroma. However, accurate assessment of atheroma volume and comparison of adjacent segments requires repeated reviews of recorded images. A number of investigators have developed 3-D IVUS techniques for efficient assessment of vascular geometry [66]. These methods make use of an IVUS transducer that is introduced into the artery under examination and advanced to the site of interest under fluoroscopic or ultrasonic guidance. To obtain the information necessary for reconstruction of a 3-D image, IVUS transducers that provide 360 tomographic views perpendicular to the axis of the probe (side-viewing) are then withdrawn (pullback approach), either manually [67] or mechanically [68, 69]. The rate of withdrawal is typically 2.5 to 5 mm/s, and the images can either be stored on video tape for later digitization and reconstruction, or directly digitized into a computer.

More recent IVUS transducers [70] provide a view forward of the transducer tip and are used in narrowed or occluded vessels, in which the side-viewing IVUS transducer cannot be inserted past the stenosis. With these forward-viewing transducers, the transducer remains fixed at one location in the artery, but is rotated along its long axis, producing the required images by rotational scanning. In both approaches, the vessel wall is identified and outlined manually or semi-automatically, and rendered in 3-D [66].

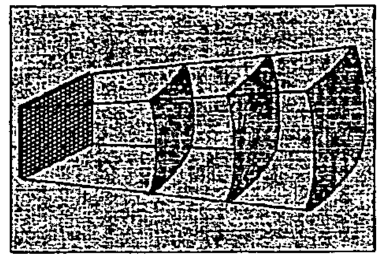
Clearly, the major advantage of 3-D IVUS is that it provides fine-resolution, detailed 3-D images of a small vascular region of interest (1-5 cm^3). The disadvantage with the pullback approach is that geometrical distortions are possible since the 3-D reconstruction is centered on the transducer. Any vascular curvature, motion of the transducer from side-to-side, or other geometric changes from a straight line are not represented accurately in the 3-D image. The forward-viewing IVUS transducer alleviates these problems; however, for fine-resolution imaging, its forward view is limited to about 1 cm [70].

The optimal choice of the rendering technique is generally determined by the clinical application.

Reconstruction

3-D image reconstruction refers to the generation of a 3-D representation of the examined structures from the acquired set of 2-D images. The reconstruction process has been implemented in two distinct ways. In the first, the series of 2-D images are segmented to extract the desired features before the 3-D image is reconstructed. For example, in echocardiographic imaging, the boundaries between the blood-filled chambers and heart tissues are outlined either manually or automatically. From the boundary descriptions, a 3-D surface model is developed and viewed by a number of techniques. This approach is also used in 3-D IVUS imaging to reconstruct the vascular lumen.

The second approach uses the acquired series of 2-D images to build a 3-D voxel-based Cartesian volume (i.e., 3-D grid) by placing each acquired 2-D image in its correct location in the volume. The gray-scale values of any voxels not sampled by the 2-D images are calculated by interpolation between the appropriate images. If the acquired images sample the volume properly according to the Nyquist Sampling theorem, then no aliasing will occur. However, if the volume is not sampled properly with a distance between acquired images that is too large, then image information will be lost. Thus, with appropriate spacing of the acquired images, all 2-D image information is preserved, allowing viewing of the original 2-D planes, as well as other views. Any segmentation to extract desired features, or to make measurements, can then be performed with the voxel-based 3-D image.



4. Schematic diagram showing a 2-D array used in the real-time 3-D ultrasound system.

The advantage of the first approach is that it reduces the amount of information, allowing for efficient 3-D rendering. In addition, it also provides 3-D images with increased contrast between segmented structures. This latter feature can also be a major disadvantage, since the process of segmentation removes "unwanted" information, thus artificially accentuating the image contrast. To avoid image artifacts, the segmentation process must be accurate — a difficult task in situations where the image contrast is low. Another disadvantage is that the segmentation phase can be time-consuming, particularly in low-contrast regions in the image.

The second approach, in which a voxel-based 3-D image is produced, makes no assumptions about the desirability of any information, therefore, no information is lost during the 3-D reconstruction. The 3-D voxel representation allows a variety of rendering techniques, such as those based on texture-mapping and ray-casting. However, this approach results in large data files that must be manipulated in real time for viewing and for measurements of geometry. Data files as large as 96 MB have been reported in 3-D prostate imaging for cryosurgical guidance [29]. The reconstruction process requires no user intervention and is easily automated. With the mechanical localizer approach for transducer motion, the 3-D scanning geometry is

known *a priori*. This permits efficient computation of many geometrical parameters, resulting in short reconstruction times.

3-D Ultrasound Rendering

Image acquisition characteristics of a 3-D ultrasound system are crucial to determine the quality of the final image. Nevertheless, the rendering technique chosen also plays an important and, at times, dominant role in determining the information transmitted to the operator by the 3-D ultrasound image display. There are many techniques for displaying 3-D images and they are divided into three classes: surface-based, multi-planar, and volume-based viewing. The optimal choice of the rendering technique is generally determined by the clinical application.

Surface-based Viewing Techniques

The most common 3-D display technique is based on visualization of surfaces of structures or organs. In this approach, a segmentation or classification step precedes rendering. In this first step, the operator or the algorithm analyzes each voxel and determines the structure to which it belongs [71]. Algorithms can be simple thresholding, or can be more complex, based on statistical and geometric properties of parts of the image. In addition, the technique can be manual, relying on the operator to determine the boundaries of structures or on automated techniques [72-74]. Once the tissues or structures have been classified, two basic methods are available for viewing: wire-frames and surface rendering.

The wire-frame approach is the simplest. In this approach, the boundaries between structures are represented by a network of lines that can be viewed in 3-D perspective. This approach has been used for displaying the fetus [16, 75-77], various abdominal structures [78-80], the endocardial and epicardial surfaces of the heart [10, 19, 50, 55, 73, 81, 82] and septal defects [51].

In the surface-rendering technique, the surfaces representations are shaded and illuminated, and at times, depth cues added, so that topography and 3-D geometry are more easily comprehended. An example of 3-D echocardiographic rendering is shown in Fig. 5, demonstrating the left and right ventricles of a five-day-old baby with a ventricular septal defect closed by a patch. Automatic rotation or user-controlled motion is generally useful to allow the operator to view the anatomy from different perspectives. This approach has been used successfully by

5. 3-D echocardiographic images of a five-day-old baby's heart with a patch used to close a significant ventricular septal defect. The patch can be seen as the bright region between the right ventricle (on the left of each image) and the left ventricle (on the right of each image). The two images are the same, with the exception that the one on the left was rendered after image mottle was reduced. The images were acquired with a transthoracic mechanical fan scanning technique and surface rendered using a TomTec system (Munich, Germany). The images are courtesy of Dr. Achi Ludomirsky.

Three different 3-D techniques have potential use in vascular imaging.

TomTec Inc. (Munich, Germany) and a number of investigators in rendering of echocardiographic [6, 7, 43, 47, 83-86] and obstetrical 3-D images [87, 88].

Multiplane Viewing

Multiplane viewing requires that a 3-D voxel-based image be first reconstructed and be easily accessible by the display algorithm. The image information can be viewed using two techniques. In the first, computer user-interface tools are provided to the operator to allow selection of planes, including oblique, from the volume for viewing as reformatted 2-D images. With appropriate interpolation, these planes may appear similar to the images that would be obtained by conventional 2-D ultrasound imaging. Often, three perpendicular planes are displayed on the screen simultaneously, with screen cues as to their relative orientation and intersection. These cues facilitate orientation of the reformatted planes and help the operator conduct the examination [26, 88-92]. This technique has been used successfully in a commercial 3-D system developed by Kretztechnik (Zepf, Austria).

A second technique is based on multiplanar visualization with texture-mapping. In this technique, the 3-D image is presented as a polyhedron representing the boundaries of the reconstructed volume. Each face of the polyhedron is rendered using a texture-mapping technique [93] with the appropriate ultrasound image for that plane. The polyhedron can be rotated to obtain the desired image orientation and then any of the faces can be moved in or out (i.e., sliced) parallel to the original, or reoriented obliquely, while the appropriate ultrasound data are texture-mapped in real-time on the new face. In this way, the operator always has 3-D

image-based cues relating the plane being manipulated to the rest of the anatomy [5, 24, 36, 58]. Figure 6 shows three examples of the use of this approach to display anatomy in 3-D. Figure 6a shows a 3-D color Doppler image sliced to reveal blood flow in the common, internal, and external carotid arteries. This image was acquired with the mechanical linear scanning method. Figure 6b shows a 3-D image of a prostate gland acquired with the mechanical rotational scanning method; and Figure 6c shows a 3-D image of a pregnant uterus with twins, acquired also with the mechanical rotational scanning method. This approach has been used successfully by Life Imaging Systems Inc. (London, Ontario, Canada) in a number of soft-tissue imaging applications.

Volume-based Techniques

Both the surface-based and multiplane techniques reduce the 3-D image presentation to a display of 2-D data by using complex or planar surfaces. Because our visual senses are best suited for surface viewing and interpretation, these two approaches are easily understood by the operator and require little learning. However, the surface-based display technique presents a small part of the complete 3-D information acquired at any one time. An alternative is the volume-based rendering technique, which presents to the viewer a display of the entire 3-D image after it has been projected onto a 2-D plane. The most common approach is to use ray-casting techniques [94-96], which project a 2-D array of rays through the 3-D image. Each ray intersects the 3-D image along a series of voxels. The voxel values for each ray can be weighted (e.g., by zero if a structure is to be removed) and then added to form a "density-weighted" image that shows the anatomy in a translucent manner. Another common approach is to display only the voxels with the maximum intensity along each ray, to form a "maximum intensity projection" image. Examples of both can be seen in Fig. 7. To obtain these images, the kidney in Fig. 7a and spleen in Fig. 7b were first scanned using a linear free-hand scanning technique, without any position or orientation information. The 3-D images were reconstructed and then rendered using a "density-weighted" technique in Fig. 7a, and a maximum intensity projection in Fig.7b.

The volume-based techniques, which display the anatomy in a translucent manner such as in an x-ray radiograph, preserve all the 3-D information, but project it (after nonlinear processing), onto a 2-D plane for viewing. Although depth cues can be added (e.g., stereo viewing), this approach results in images that are difficult to interpret. Thus, this approach is best suited for simple anatomical structures in which clutter has been removed. A number of investigators have demonstrated successful applications, particularly in displaying fetal [27, 28, 88, 97-99] and vascular anatomy [30, 100].

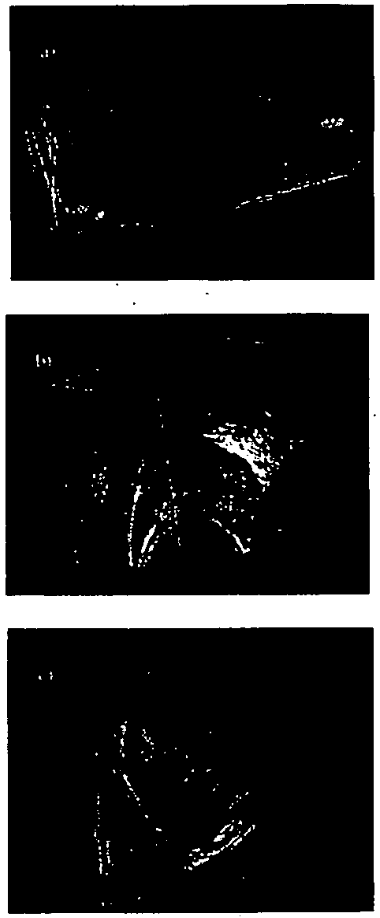
Diagnosis of congenital heart disease is greatly facilitated by dynamic 3-D viewing

Applications

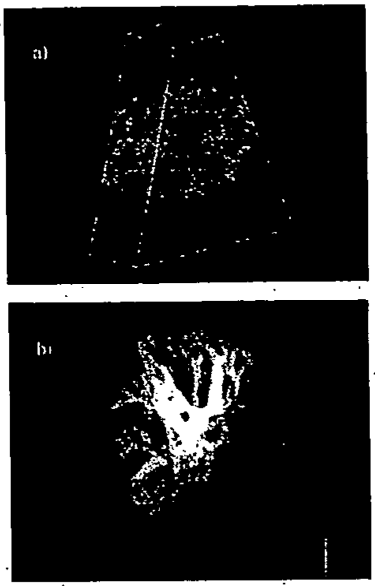
Although 3-D ultrasound imaging has been investigated for over a decade, it is only now being seriously considered as a practical imaging modality for everyday clinical use. Improvements in reconstruction algorithms, display techniques, and computer power account for the increasing clinical interest. Recent studies have shown that the use of 3-D ultrasound results in accurate assessment of volumes and a display of information in a manner that has not previously been possible with conventional techniques [58]. Another advantage is shorter patient examination times. In conventional sonography, the examiner repeatedly interrogates the same volume of tissue to build up a mental image of the 3-D structure. With 3-D ultrasound, a single sweep of the ultrasound probe is usually sufficient to reconstruct the entire volume, which can than be repeatedly examined after the patient departs. Thus, the patient examination time is reduced and the physician can interrogate the volume with a computer in an appropriate manner.

Vascular Imaging

Three different 3-D techniques have



6. Three 3-D ultrasound images rendered using the multiplane viewing technique developed by Life Imaging System Inc. (London, Canada). a) 3-D color Doppler image of the carotid arteries obtained using the mechanical linear scanning technique. The acquisition was cardiac gated at peak systole so that an ATL linear array transducer was moved 0.5 mm every heart beat until 140 images were acquired in about 2 minutes. b) 3-D image of a patient's prostate gland after a transurethral resection procedure (TURP) obtained using a mechanical rotational acquisition technique. To obtain the image, an ATL transrectal probe was mounted in a LIS assembly and rotated through 200° while 200 images were acquired in about 13 sec. c) 3-D image of seven-week-old twins, obtained using a mechanical rotational acquisition technique. To obtain this image, a Siemens endo-cavity probe was mounted on the same assembly, as in Fig. 6b, and rotated through 200° while 200 images were acquired in about 13 sec.



7. Two power Doppler 3-D ultrasound images rendered using volume-based techniques. The 3-D images were obtained using a linear free-hand scanning technique, reconstructed and then rendered. For details see [30]: a) shows a density sum image of the kidney. b) shows a maximum intensity projection image of the spleen.

potential use in vascular imaging. B-mode 3-D imaging, obtained from a transducer placed on the skin or within the vessel, has the potential to give an accurate representation of plaque within the vessel wall and to determine quantitative plaque volume and stenosis degree assessment. Color Doppler imaging has the potential to show physiological information with regard to flowing blood [37]. Because carotid artery stenosis in excess of 70% may require surgery, the medical community is interested in a more clear means of noninvasively identifying these patients. Similarly, stenotic lesions in the peripheral arteries are often assessed with angiography. This is an invasive procedure involving contrast material, with potential severe complications. Should 3-D ultrasound decrease the number of patients requiring angiography, a major benefit would be achieved. The third technique showing promise for vascular imaging is 3-D power Doppler. The images produced by this technique are similar in appearance to the images obtained with MR angiography. Though lacking the accurate anatomical detail associated with angiography and CT, initial images appear to show good qualitative information [30]. 3-D power Doppler imaging of the microvasculature is of potential value and has been shown to have the capability of displaying some abnormal tumor vessels [30].

Soft Tissues

Recent publications have focused on the ability of 3-D ultrasound to measure volumes accurately [26, 58, 101]. Accurate calculation of the prostate volume is essential to estimate whether a serum PSA test could be considered highly suspicious for cancer. Volumetric assessment of fetal size is also highly desirable in assessing cases of retarded intrauterine growth. In addition, the biological activity of various tumors can be correlated with their true size and, therefore, an accurate volumetric assessment is highly desirable for monitoring the tumor's response to treatment.

In surgical planning, knowing the relationship of a structural abnormality to known landmarks is very helpful. With conventional ultrasound, it is up to the skill of the sonographer to ensure that any two structures are imaged in the same plane. With 3-D ultrasound, the relationship can be more clearly shown. Some examples for specific locations include:

1. Eye and orbit: The technology has undergone some initial assessment and has shown some potential in measuring tumors accurately, in displaying the extent of vitreous and retinal disease, and in surgical planning [33, 48, 49, 102].

2. The fetus: 3-D ultrasound can be useful for assessing the fetus [16, 27, 28, 77, 87-89, 97, 98]. Sonography is widely used in the second trimester for the assessment of fetal abnormalities. Having the ability to perform accurate surface rendering is likely to improve the diagnostic accuracy in assessing subtle abnormalities such as cleft lip.

3. The kidney: One area of potential application is imaging intrarenal neoplasia of the native kidney, especially in patients with a solitary kidney. In instances where renal sparing surgery is considered, a clear understanding of the anatomy is highly desirable. A second area of potential application is imaging of the transplanted kidney. As rejection develops, transplanted kidneys are known to increase in size and develop flow patterns that are abnormal and not uniformly distributed throughout the kidney. These changes are difficult to appreciate with 2-D ultrasound, but 3-D images may provide a more accurate way of demonstrating them [30].

The goal of developers is to provide dynamic 3-D images immediately after the exam.

4. The liver: Though 3-D ultrasound images of the liver have been produced, this organ presents several technical challenges [100]. The liver is large (approximately 15 x 16 x 12 cm^3), it is sheltered behind the lower ribs, it moves considerably with respiration, and its left lobe moves with cardiac motion. Selective 3-D imaging of portions of the liver may provide a greater promise of success. 3-D imaging might be utilized in guiding invasive procedures in the liver, such as cryosurgery [29], or in surgical planning. Power Doppler imaging of the portal venous system and hepatic veins has also been shown to be technically possible, but its clinical utility is not yet known [30].

5. The Breast: While traditional sonography can easily demonstrate breast cysts, the topographical properties of breast lesions have immense prognostic significance to determine whether specific lesions are likely to be benign or malignant and whether a biopsy is required. The vast majority of lesions currently biopsied tend to be benign, but 3-D ultrasound has the potential to demonstrate the margins of these lesions, and therefore, to reduce the need to biopsy benign masses [40, 46].

6. Tumors: Malignant tumors induce neovascularity, which may be detectible with power Doppler imaging. Because tumors induce the formation of abnormal blood vessels with tortuous patterns and high-velocity blood flow, the combination of power Doppler imaging and 3-D ultrasound may prove to be a diagnostically useful tool for tumor detection and evaluation [30, 31, 39].

Cardiology

The heart is a geometrically complex structure that moves with the chest cavity, due to both cardiac activity and respiration. Useful 3-D imaging of the heart requires a cine sequence of views that is respiration gated during the cardiac cycle (dynamic 3-D imaging). Dynamic 3-D viewing of the heart allows the physician to view the dynamic anatomy, spatial relationships of normal and abnormal structures, and flow disturbances. Also, these images permit the calculation of a range of useful quantitative parameters. Many investigators have attempted to measure left ventricular volume in an accurate and reproducible manner. Transthoracic and transesophageal approaches have been used to obtain dynamic images of changes in chamber volume through the cardiac cycle. These measures are used in calculation of ejection fraction in ischemic and congenital heart disease.

Another important diagnostic use is the display of geometrical relationships between normal and pathological structures. Viewing the mitral and aortic valves throughout the cardiac cycle is important to understanding their morphological features. Diagnosis of congenital heart disease is greatly facilitated by dynamic 3-D viewing of ventricular and atrial septal defects, as well as other congenital defects related to the valves and major blood vessels. Viewing the 3-D anatomy in the computer enables the physician to visualize the relevant structures with a perspective similar to that found during surgery, facilitating the surgical plan,, particularly in cases of congenital pathology.

The Future

The possibility of producing 3-D images has been explored since the advent of ultrasound imaging. Only in the past few years has computer technology and visualization techniques become sufficiently advanced to make 3-D ultrasound imaging efficient and permit its migration from the research laboratory to the examination room. However, for 3-D ultrasound imaging to come into widespread routine clinical use, a number of further advances must be realized.

First, before 3-D imaging is accepted as a routine tool, diagnosticians must make the transition from viewing 2-D ultrasound images on the ultrasound machine, film, or video tape, to viewing 3-D images on a computer monitor. This change requires education and training, leading to a cultural change in medical diagnosis. To exploit the 3-D image, the diagnostician needs to be able to accept the paradigm shift of performing the examination in the computer rather than on the patient.

Second, to permit optimal use of the 3-D system and to avoid interference with efficient patient management, a number of systems improvements are required, with the user-interface being foremost. Diagnosticians and sonographers must be able to interact with the system in an intuitive manner, without a difficult learning curve. Thus, the 3-D system's user-interface must resemble a medical instrument and not a computer program, i.e., the user interface must not intimidate the user with an extensive selection of icons and multilevel menus. Third, to enhance patient management and to minimize waiting time, substantial improvements in reconstruction and display speed must still be achieved *without* incurring additional cost in hardware. The goal of developers is to provide dynamic 3-D images immediately after the exam.

These improvements require substantial effort, but based on the rapid changes in the utility of 3-D ultrasound imaging in the past few years, clearly these advances are possible. Their achievement can lead to the routine and efficient use of 3-D ultrasound in radiology and echocardiology.

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Dr. Aaron Fenster is the Director of the Tom Lawson Family Imaging Research Laboratories of The John P. Robarts Research Institute in London, Canada. This laboratory has about 65 individuals pursuing research in diagnostic radiological imaging, including CT, MRI, ultrasound and digital x-ray imaging. The laboratory works closely with industry and has filed for about 15 patents in the past five years. Dr. Fenster is also a professor in the departments of Radiology, Medical Biophysics, Physics, Electrical Engineering, and Radiation Oncology. His present research interest is focused on the development of 3-D ultrasound imaging systems for radiology as well as cardiology. A number of the systems developed in Dr., Fenster's laboratory are now in multicentered clinical trials evaluating their efficiency. Dr. Fenster has over 110 peer-reviewed publications and 12 patents.

Dr. Donal Downey is a staff radiologist and Director of Diagnostic Ultrasound at University Hospital (London). He is an Assistant Professor at The University of Western Ontario and an Associate Scientist at The John P. Robarts Research Institute, with 24 peer-reviewed articles and 2 patents. In the past 4 years his research focus has been on 3-D ultrasound imaging for both diagnostic applications as well as for minimally invasive ultrasound-guided procedures.

Address for Correspondence: Aaron Fenster, Ph.D., FCCPM, The J. P. Robarts Research Institute, Imaging Research Laboratories, 100 Perth Drive, London, Ontario N6A 5K8, CANADA.

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